IMPLEMENTATION OF THE α-CHERS DIAGNOSTIC FOR D-T OPERATION OF TFTR

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ABSTRACT:

The α-CHERS diagnostic is a high throughput charge exchange recombination spectroscopy diagnostic designed to measure the density profile and time evolution of 0-500 keV alpha particles during D-T operation of TFTR. Following successful tests with a prototype α-CHERS system, an improved, multi-channel system has been installed for D-T Operation. Three spatial channels may be observed simultaneously, and the spectral resolution of 0.5 nm permits increased alpha energy resolution and improved impurity line identification. More efficient coupling optics between the spectrometer and CCD detectors have increased the light throughput, and radiation shielding has been installed around the detectors and spectrometers to eliminate the neutron/gamma ray noise observed in high power D-D plasmas.

I. INTRODUCTION

A central goal of the TFTR D-T experiments is to study alpha particle physics in a reactor-grade plasma. In particular, confinement and transport of the fusion-produced alpha population, alpha heating of electrons, and potential alpha-driven instabilities will be studied. To aid in these studies, several confined and lost alpha particle diagnostics have been installed on TFTR[1,2,3].

α-CHERS is a charge exchange spectroscopy diagnostic designed to observe confined alphas with energies in the range from thermal values to approximately 500 keV [4,5]. Alpha particles are observed by measuring the Doppler-shifted n=4-3 transition of He^{+1} near 468.6 nm, which is excited by electron exchange reactions between the neutral beam atoms and alpha particles. Analysis of this spectrum is expected to yield the spatial density profile, time evolution and perhaps the energy distribution of the alphas.

The unique attributes of α-CHERS are very high light throughput and a high-efficiency, low-noise, high-dynamic-range detector, all of which are necessary to observe the very weak alpha signal. This paper describes the α-CHERS instrumentation as modified for D-T operation of TFTR, and shows test results during D-D and D-T operation.

II. α-CHERS DESIGN AND INSTRUMENTATION

The prototype α-CHERS system has been described previously [4,5]. The charge-exchange cross-section for excitation of the 4-3 transition of alpha particles with the 50-60 keV/amu TFTR neutral beams is significant for alphas with an energy of $E_\alpha \leq 0.5$ MeV. The resulting spectrum is Doppler-shifted from 468.6 nm to longer wavelengths as a result of the beam-sightline viewing geometry. It extends over a spectral region of approximately 10 nm and its intensity is predicted to be approximately 0.1% to 1% of the visible bremsstrahlung (VB) continuum.

A schematic diagram of α-CHERS is shown in Figure 1. A central challenge is the extraction of the low intensity alpha signal from the much more intense VB continuum. To achieve the necessary photon statistics-dominated noise level, a very high throughput spectrometer (1.4×10^{-2} cm^2-ster) is coupled to a back-illuminated, low-noise charge coupled device (CCD) camera. The CCD detectors are thermoelectrically cooled and have a quantum efficiency of 60%-70% at 470 nm. They also have very high dynamic range (16-bit) and a low readout noise (about 25 e^-/pixel). Time resolution, limited by the detector readout time, is 50 ms or longer.

Five radial channels can be observed at each of two ports on TFTR, one tangentially viewing a co-directed beam and the other vertically viewing a counter-directed beam, potentially allowing for velocity space anisotropy and interfering ion plume measurements. Radial channels are spaced 10 cm apart and have a resolution of 2-3 cm. Each channel consists of 10 1-mm diameter quartz fibers filled at f/2.0 by the viewing optics on TFTR. A 60 meter run of fiber carries the light to the remotely located spectroscopy system. A pair of achromatic lenses (f/2 and f/4) match the light to the f/3.8 0.275 m. spectrometer. The 42 mm x 42 mm output spectrum is then imaged onto the 14 mm x 14 mm CCD with 3:1 reducing lenses.

The prototype single-channel system successfully observed ^{3}He ions with energies up to 300 keV produced by ICRF heating [6]. However, the D-T alpha signal is expected to be weaker than the ^{3}He ion RF tail signal, so several design changes were implemented to improve the sensitivity of the multichannel α-CHERS system on TFTR.

The full α-CHERS diagnostic contains three spectrometer systems, thus providing measurements from three of the five available spatial channels in a given discharge. This allows for partial radial coverage in one shot and total coverage during two similar shots.

An important aspect of the data analysis is the identification of several low intensity impurity lines in the spectral range of interest (468-480 nm), emitted predominantly by edge carbon and helium ions. To facilitate the identification and removal of these lines from the spectrum, the spectral resolution has been improved from 1.0 nm to 0.5 nm by using a 3600 g/mm grating instead of the 2400 g/mm grating used in the prototype system. The 3600 g/mm grating provides about 65% of the light throughput of the 2400 g/mm grating. α-CHERS uses a wide spectrometer entrance slit (700 microns) to provide the necessary light throughput. The 4 cm entrance slits are curved (10.5 cm radius of curvature) to correct for the spectrometer line curvature, yielding a vertical output slit image.

The prototype α-CHERS system used a coherent 3:1 fiber optic taper and a pair of 1:1 imaging relay lenses to image the output focal plane onto the CCD chip. Significant light loss occurred in the reducing fiber optic taper (30%-50% transmission) and moderate vignetting occurred in the relay lenses. The output optics imaging system was redesigned to achieve approximately 90% light throughput using a field lens and 3:1 camera lens imaging system. A 150 mm, f/2 field (plano-convex, simple) lens is located approximately 5 mm behind the output spectrometer focal plane. A medium-format camera lens (Pentax 150 mm, f/3.5) collimates the light bundle. An additional camera lens (Nikon 50 mm, f/1.2) then images the spectrum onto the CCD. The net effect is a factor of three improvement in total light throughput over the original taper/relay lens configuration.

The present three channel system maintains a 100% duty cycle at 50 ms time resolution by keeping the shutters open all the time, even during CCD readout, and performing complete on-chip binning in the vertical (spatial) direction of 512 pixels to one superpixel. This results in a smearing of the data over a readout time giving a trapezoidal temporal instrumental function. Elimination of shutter cycling was also found to prevent systematic noise introduced by jitter in the shutter operation. 200 ms time resolution is expected to be sufficient to observe the evolution and thermalization of the alpha population, given the 500-700 ms alpha particle slowing down time in TFTR.

III. RADIATION EFFECTS AND SHIELDING

Given the low intensity of the α-CHERS signal, operation in the intense neutron and gamma radiation environment produced near a D-T tokamak presents several problems. One potential difficulty is radiation effects on the fiber optics[7,8]. Fibers fluoresce under exposure to intense gamma radiation as a result of Cherenkov radiation from Compton electrons generated through scattering of gamma rays within the bulk of the fibers. The fluorescence appears as a continuum which slowly increases in intensity towards shorter wavelengths. The intensity of the continuum depends on the routing of the fibers within the radiation environment, and, in particular, how much fiber length is in close proximity to the vacuum vessel where the gamma flux is the highest.

The intensity of the fluorescence is about 5% to 10% of the VB continuum at 469 nm in a high power D-T discharge. The additional photon noise due to the fluorescence will have negligible effect on the total uncertainty of the measurement. Optical fibers with opaque endcaps have been installed with identical routing as the light transmitting fibers and will be used for direct measurement of the fluorescence, which can then be incorporated into the data analysis.

A second radiation effect on the fibers is reduced transmission in the neutron environment. Initial measurements indicate that this reduction in transmission is at most a few percent and is therefore not a major concern. A loop of fiber has been installed running from a stable calibration light source to TFTR and back to the spectrometers. This fiber loop will be used to make direct measurements of fiber transmission loss.

It was discovered that even the weak radiation flux at the location of the spectrometer/camera system, which is separated from TFTR by approximately 40 meters and a 1-2 meter borated concrete wall, is sufficient to generate noise spikes in the CCD detectors during D-D operation of TFTR. These radiation spikes show up as very intense (several thousand photoelectron amplitude) spikes which are 1-3 pixels wide. Extrapolation to D-T operation indicated the number of radiation spikes would make it impossible to extract the alpha signal. Consequently, a radiation shield has been installed around the spectrometers and detectors. The shield consists of 10 cm of lead and 5 cm of borated polyethylene to shield against gamma rays and neutrons, respectively.

IV. Data Analysis / Photon Noise Limited Performance

A critical requirement for making alpha distribution measurements is that the noise in the binned signal be photon-noise-limited. The signal-to-noise ratio of the alpha signal is estimated to be approximately 5-10 for high performance D-T plasmas in TFTR with alpha densities of about 2.0×10^{17} m^{-3}, assuming that all noise is due to photon statistics. This SNR is achieved by binning together the signal from 30 pixels, equivalent to approximately 1.0 nm of spectral data. This still allows for an energy resolution of at least 30 keV over the 100-500 keV observable energy range.

Detailed analysis of the noise behavior indicates that the data is photon noise limited over a wide range of signal intensities. Measurements of the VB signal during plasma operation, which are an order of magnitude lower in intensity than the calibration lamp illumination, have been analyzed and shown to also have a noise level dominated by photon statistics. The electronic readout noise, at 20-30 e^-/pixel, is far below the photon noise in all measurements.

Given the lack of modulation in the TFTR heating beams, the small fast-alpha signal may be most accessible by comparing similar D-D and D-T discharges. The data are normalized at a VB-only spectral region to account for shot-to-shot variations. Photon-statistics-limited noise performance is maintained when subtracting spectra from similar D-D and D-T discharges to extract weak spectral features. Figure 2 shows a sample spectrum taken during an ICRF ^{3}He minority heating experiment with 5 MW of injected RF Power. The extracted fast ^{3}He ion signal is shown in figure 3 where ions with energies of up to 250 keV are observed.

An important aspect of the data analysis is the need to accurately model the impurity lines that appear in a typical spectrum. Several carbon, helium and other impurity lines show up in the spectral range of interest (465-482 nm). The impurity lines are modeled as single Gaussian line shapes on a linear background convolved with the measured instrumental function. The thermal helium line at 468.6 nm is treated similarly but as a double Gaussian to account for the hot core and cool edge components.

In order to make absolute measurements of the alpha particle density, it is necessary to absolutely calibrate the entire system. This calibration is accomplished with a two-step process. First, the absolutely calibrated spectral radiance source illuminates the spectrometer/detector system through an assembly of fibers similar to those from TFTR. This provides an absolute calibration of the local spectrometer/detector system. Any light losses that occur in the TFTR collection optics and in the 60 meter fiber run are corrected for by measuring the VB as seen by α-CHERS at a line-free spectral region near 480 nm and cross-calibrating with the VB as measured by the TFTR Z_{eff} diagnostic, known as HAIFA[9].

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FIGURE CAPTIONS

1. Schematic diagram of the α-CHERS diagnostic with associated data acquisition and control equipment.

2. Spectrum from ICRF ^{3}He minority heating experiment.

3. Intensity of the ^{3}He RF tail signal as a function of particle energy.

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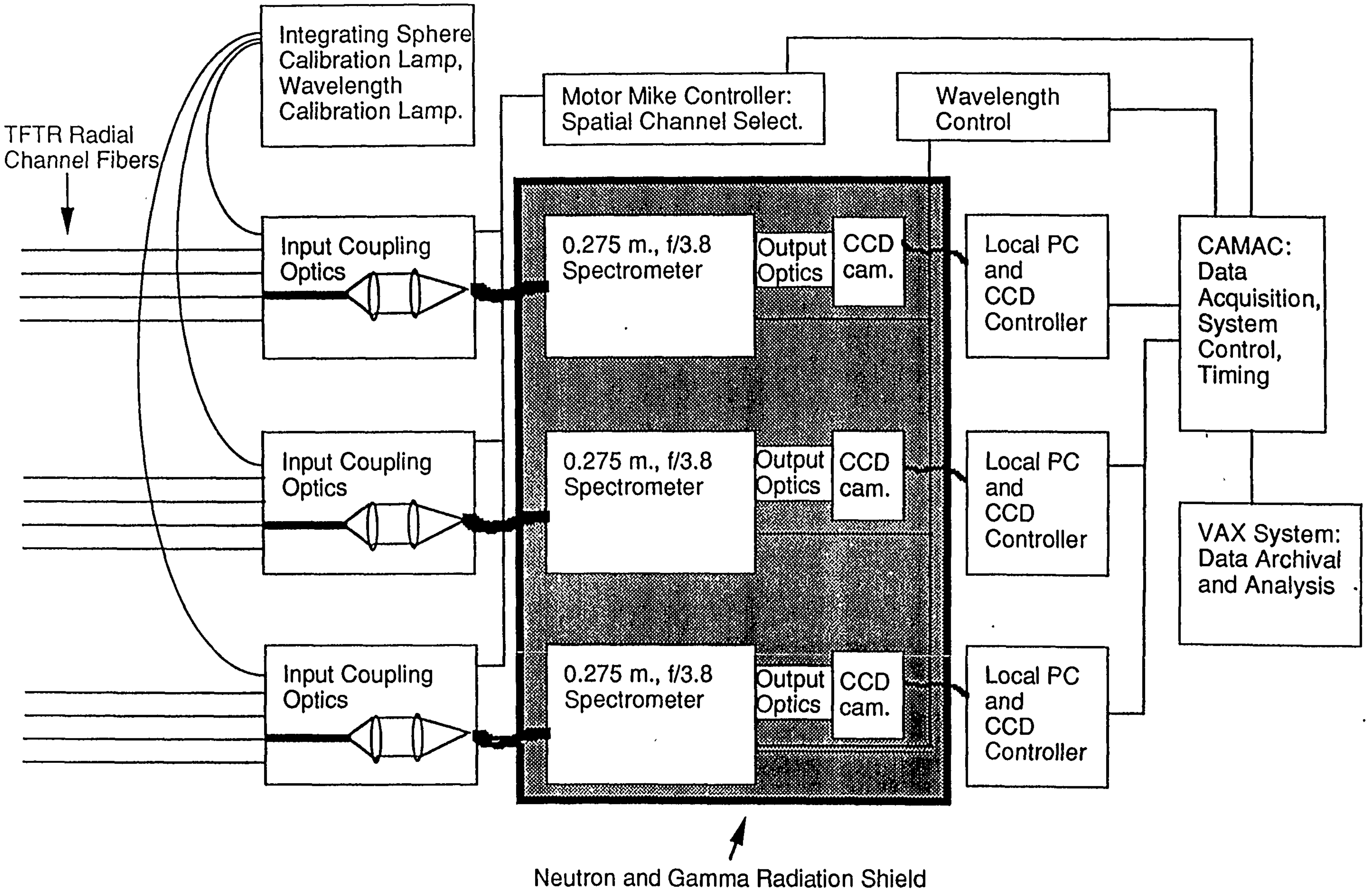
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Wavelength
Calibration Lamp.
Motor Mike Controller:
Spatial Channel Select.
Wavelength
Control
TFTR Radial
Channel Fibers
Input Coupling
Optics
0.275 m., f/3.8
Spectrometer
Output
Optics
CCD
cam.
Local PC
and
CCD
Controller
CAMAC:
Data
Acquisition,
System
Control,
Timing
Input Coupling
Optics
0.275 m., f/3.8
Spectrometer
Output
Optics
CCD
cam.
Local PC
and
CCD
Controller
VAX System:
Data Archival
and Analysis
Input Coupling
Optics
0.275 m., f/3.8
Spectrometer
Output
Optics
CCD
cam.
Local PC
and
CCD
Controller
Neutron and Gamma Radiation Shield

Fig. 1

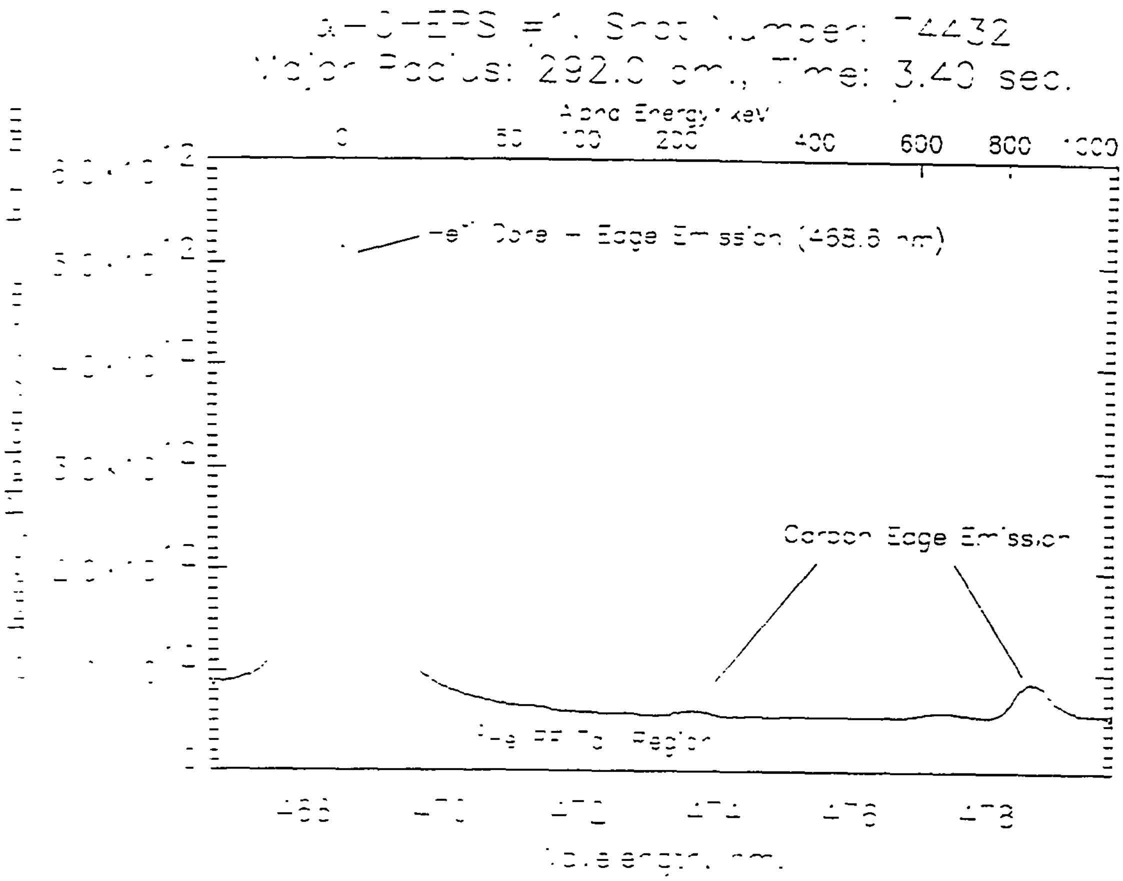
α-CHERS #1, Shot Number: 74432
Major Radius: 292.0 cm., Time: 3.40 sec.
Alpha Energy, keV
0
50
100
200
400
600
800
1000
HeII Core - Edge Emission (468.6 nm)
Carbon Edge Emission
He RF Tail Region
468
470
472
474
476
478
Wavelength, nm

Fig. 2

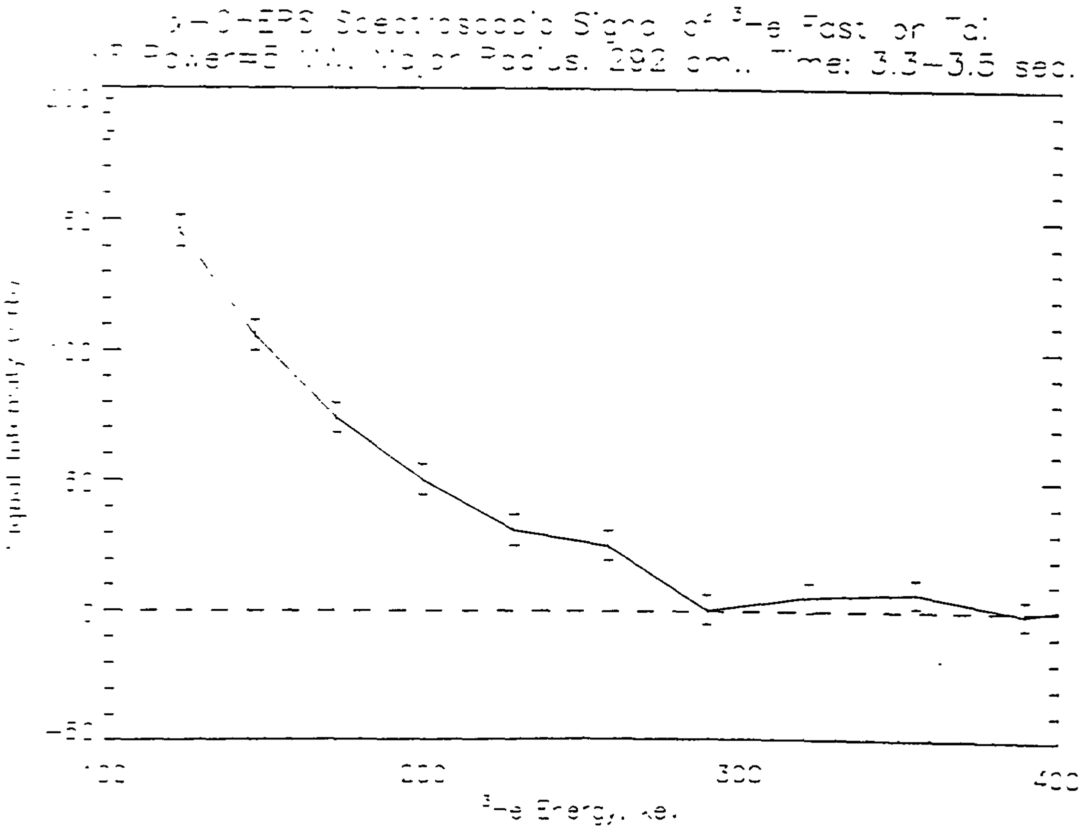
α-CHERS Spectroscopic Signal of 3He Fast Ion Tail
RF Power=5 MW, Major Radius: 292 cm., Time: 3.3-3.5 sec.
200
150
100
50
0
-50
Signal Intensity (arb)
100
200
300
400
3He Energy, keV

Fig. 3

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